Pulse dispersion measurements in conventional Selfoc fibers

Harish R. D. Sunak

Measurements of pulse dispersion in conventional Selfoc fibers have been carried out. The principal light source was a pulsed mode-locked ruby laser. Qualitative agreement has been found with theory, which predicts multimode operation and, hence, large pulse dispersion in such fibers under greatly mismatched launching conditions. Under such conditions, we have observed dispersion equivalent to ~20 nsec/km.

Introduction

Communication systems using optical fibers are now practically and economically feasible as fibers with low loss and large bandwidth have been made, and significant advances in the various devices needed in such systems have also been achieved.[1] Besides other fiber types, there is great interest in fibers that have a continuous radial decrease of refractive index from the fiber axis. These are referred to as graded-index fibers. The Selfoc fibers[2] (trade name of fibers made by the Nippon Sheet Glass Company, Japan) were the first graded-index fibers. Scanning the literature, it is surprising to note the few reports of dispersion in these fibers. Such dispersion measurements were first carried out by Bouillie and Andrews[3], who detected 12 psec in 20 m (i.e., 0.6 psec/m). Then Gloge *et al.*[4] reported 100 psec in 70 m (1.4 psec/m). Koizumi *et al.*[2] detected 300 psec in 1 km (0.3 psec/m). These discrepancies in the measurements can be partly elucidated by the theoretical analysis made by Gambling and Matsumura[5] in terms of the mismatch that could occur leading to excitation of higher-order modes when launching into such a fiber, i.e., the Selfoc fiber behaves like a multimode fiber.

We have made complementary measurements[6] on Selfoc fibers with the aim of investigating further the validity of this analysis; this paper reports the results obtained and hence is a contribution toward the sparse literature that exists on the bandwidth of these fibers. The main interest was to launch the laser light with a large mismatch and to see whether a large dispersion was obtained as predicted by theory.[5] Such measurements using a ruby laser are reported here for the first time. Guttmann *et al.*[7] subsequently also measured dispersion in new Selfoc fibers, and their results will be discussed later in the paper. All these mentioned measurements are summarized in Table I. They have been carried out on two different types: conventional and new Selfoc fibers. The former are produced as follows: a mother Selfoc rod is first prepared by diffusion in a bath, and a fiber is pulled from this rod. The latter are produced continuously[2] using a double crucible technique, where the diffusion occurs rapidly between the molten core and cladding glasses.

Experimental Setup and Procedure

The experimental arrangement to measure dispersion with a mode-locked ruby laser[8] is shown in Fig. 1. Since the repetition rate of the laser was ~1 Hz, a sampling oscilloscope normally used with dispersion measurements could not be used, as many pulses are required to give a trace. Hence a real-time oscilloscope, Tektronix model 7904 with 500-MHz bandwidth (risetime = 0.7 nsec), was used. The photodetector used was Tropel 330 having a risetime of 0.3 nsec. Since the laser produced[8] 25-psec pulses, the system response was ~0.8 nsec, as verified using 30 cm of fiber. Figure 2 shows the result obtained. The fiber ends were prepared carefully and inserted into fiber mounts[9] so that accumulation of dust particles on the ends was avoided.

The other light source used was a GaAs laser (λ = 904 nm), which was operated[10] to give pulses of ~200 psec in duration. The optics used were similar to those shown in Fig. 1. The output pulses were detected by an avalanche photodiode and displayed on a sampling oscilloscope. The system response was ~0.4 nsec, again verified with 30 cm of fiber.

The author is with Universidade Estadual de Campinas (UNICAMP), Instituto de Fisica, Campinas-13100, Sao Paulo, Brazil.
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Table I. Summary of Pulse Dispersion Measurements made with Selfoc Fibers

Reference	Fiber length m	Fiber diameter μm	Test wavelength nm	Effective dispersion psec/m
3	20[a]	180	900	0.6
4	24[a]	100	900	1.4
	44	(10%		
	70	variation)		
2	500[b]	150–250	1060	0.3
6	60[a]	98	694	~20
	60	98	904	2.5
7	100[b]	30	~850	13.1
	700	(core diameter)	~850	11.4

[a] Conventional Selfoc fiber.
[b] New Selfoc fiber.

Results

The results were obtained using conventional Selfoc fibers. The rods were supplied by Nippon Sheet Glass Company, and the fibers were pulled at Southampton University. The fibers had 98-μm o.d. and were wound on expanded polystyrene drums of 45-cm diam for convenient handling. A length of 60 m was tested.

For the first experiment, the output of the ruby laser was attenuated to avoid damage and nonlinear effects and was coupled into the fiber with a 10× microscope objective. The launching spot size at the fiber input was ~3 μm. The cladding modes were stripped by dipping the fiber into an index-matching liquid at the input and output fiber ends. The output pulse at the end of a 60-m long fiber revealed no change compared with that measured after 30 cm of fiber, indicating that the dispersion for this length was <0.8 nsec, as shown in Fig. 3(a). A dispersion of ~1 nsec has to occur in the fiber so that, when convolved with the system response time, a change of one small division corresponding to 0.4 nsec can be observed in the output pulses on the oscilloscope.

For the second experiment, no coupling lens was used, and the laser output was only slightly attenuated. The spot size at the fiber input was 0.9 mm, much larger than the characteristic spot size of the fiber. Since the divergence of the beam was 0.5 mrad[8] and the fiber was ~50 cm from the output mirror, the launching wave vectors could be assumed to be parallel with the fiber axis. The coupling into the fiber was not efficient (<0.2%). However, this was done to set up a large mismatch launching condition and was easily possible with the high-power ruby laser. The output pulse shape consistently revealed a distinct change, especially on the trailing edge, which had a longer fall time than in the first experiment. This can be clearly seen in Fig. 3(b). Hence, we concluded a definite broadening in the output pulses in our second experiment. As discussed above, the dispersion caused by the fiber was at least of the order of 1 nsec at the half-peak power points. From Fig. 3(b), if the $1/(e^2)$ times maximum power points were considered, a higher value of dispersion would be obtained. Averaging over the fiber length, we obtain ~20 psec/m.

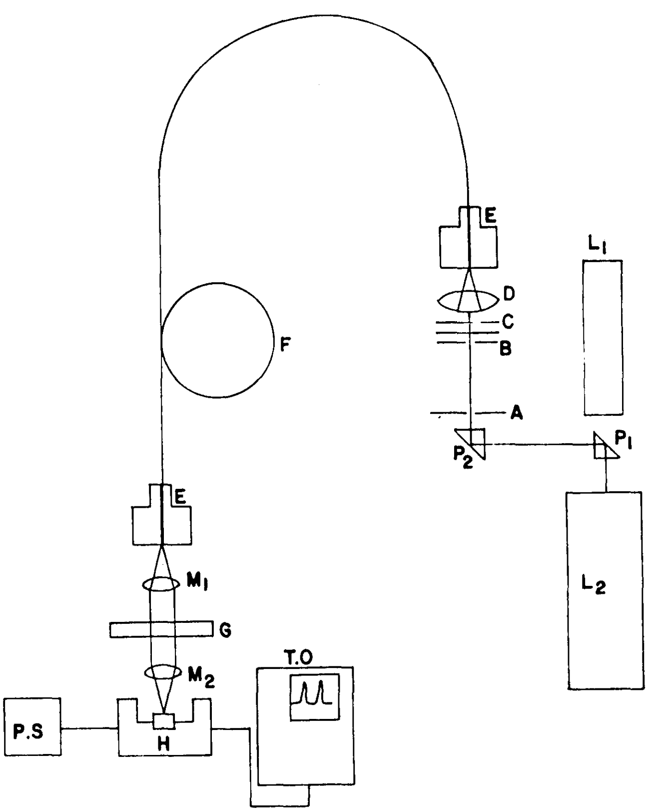

Fig. 1. Experimental arrangement for measuring pulse dispersion with a mode-locked ruby laser: L_1 represents the He–Ne alignment laser; L_2 represents the ruby laser; P_1, P_2 are prisms (BK7 glass); A, B are apertures (removed after alignment of the ruby output beam); M_1 represents the microscope objective (45×); M_2 represents the microscope objective (10×); C represents the neutral density filters; D is the coupling lens or objective; E is the fiber mount with index-matching liquid; F is the fiber; G is the narrowband filter at 694 nm; H is the Tropel 330 photodetector; $P.S.$ is the power supply (180 V) for the detector; and $T.O.$ is the Tektronix oscilloscope 7904.

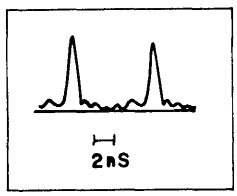

Fig. 2. Response of the detection system to mode-locked ruby pulses measured through 30 cm of fiber.

A third experiment, subsidiary to the main theme, was carried out with the GaAs laser to repeat one of the earlier experiments,[4] with a source that is of great interest in practical systems. The launching spot size was 140 μm × 35 μm; it is asymmetric due to the construction of the laser. The output pulses from 30 cm of fiber were recorded and compared with the response of a

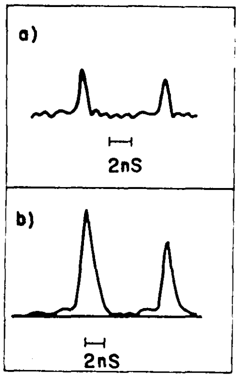

Fig. 3. Output pulses at 694 nm after 60 m of conventional Selfoc fiber: (a) $W \approx 1$ at launching, and (b) $W \ll 1$ at launching.

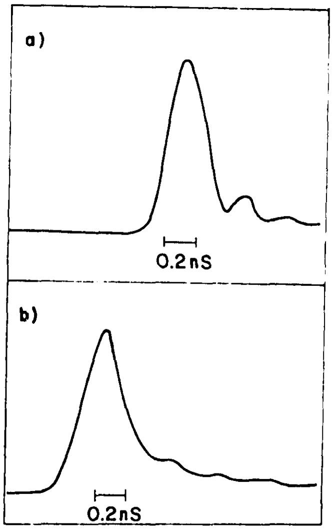

Fig. 4. Output pulses at 904 nm after different lengths of conventional Selfoc fibers: (a) $L = 0.3$ m, and (b) $L = 60$ m.

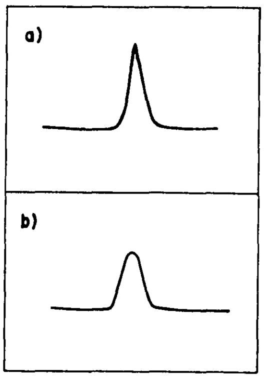

Fig. 5. Output angular distribution at 694 nm from 60 m of conventional Selfoc fiber: (a) $W \approx 1$ at launching, and (b) $W \ll 1$ at launching.

60-m fiber. The traces obtained are shown in Fig. 4. In the latter experiment we again observed a distinct and repeatable broadening compared with the former measurement. Further, the pulse shapes were also markedly different. After deconvolution, we calculated a dispersion of 2.5 psec/m.

Discussion

If ω_0 is the characteristic spot size[5] of the fiber and ω_i is the spot size of the input beam having Gaussian spatial distribution, the parameter $W = \omega_0/\omega_i$ determines the pulse dispersion in a Selfoc fiber with no mode conversion. Figure 4 of the paper by Gambling and Matsumura[5] predicts that, for $W = 1$, the Selfoc fiber behaves like a single-mode fiber whereas, for $W > 1$ or, in particular, for $W \ll 1$, higher-order modes are excited, and the Selfoc fiber can behave like a multimode fiber. Values of ω_0 are typically[5,11] of the order of 3–10 μm. Therefore, the condition $W \sim 1$ can readily be achieved in the laboratory by coupling the light with a microscope objective of appropriate focal length, as has been reported (see Table I). The discrepancies in these results can be partly explained by different W at launching—and hence different mode excitations—and partly by different amounts of mode conversion that may have occurred within the fiber, as explained below.

In our first experiment, we repeated these conditions ($W \approx 1$) and did not observe any broadening due to the system response. Hence, the dispersion was <13 psec/m. However, our second experiment had $W \ll 1$ (as $\omega_0 \approx 5$ μm and $\omega_i = 0.9$ mm), which has been carried out for the first time and is of interest as theory[5] predicts that dispersion increases rapidly as $W \rightarrow 0$. As we observed a comparatively high dispersion (~20 psec/m) with only 60 m of fiber, this result is in good qualitative agreement with the theoretical predictions. (A quantitative assessment was not attempted as such large launching mismatches will not occur in practical conditions and hence is not interesting for the systems designer.)

We expected a distinct difference in the angular distribution of the light from the fiber in the two above conditions, i.e., $W \approx 1$ and $W \ll 1$, as a distinct pulse broadening was observed in the latter case. These measurements were performed with a photodiode array, and the results are shown in Fig. 5. For $W \approx 1$, it was important to launch axially, with the spot positioned concentric with the fiber axis to obtain the peak amplitude on the axis. Lateral displacement caused a drastic reduction of the peak. For $W \ll 1$, the positioning was not critical, as could be expected. The width of the output distribution in Fig. 5(b), with $W \ll 1$, is greater at all intensities compared with that obtained in Fig. 5(a), with $W \approx 1$, and indicates that more light traveled at higher angles with respect to the fiber axis (higher-order modes) and hence led to a larger dispersion in the former case. These results also show clearly that the effect of mismatched launching is greater than mode conversion in the particular fiber under investigation, and the dispersion is dominated by the group velocity differences between the propagating modes.

The measurements with the GaAs laser also had $W < 1$, since one of the laser dimensions was 140 μm. However, the magnitude of the mismatch is not so great as with the ruby laser, and it is not surprising that we observed dispersion approximately an order of magnitude smaller. It is interesting to note that our experiment corresponds almost exactly to that of Gloge *et al.*,[4] and our results also agree well with their results.

Our results, using the GaAs laser with the conventional Selfoc fiber, are approximately an order of magnitude higher than the results of Koizumi *et al.*[2] using the new Selfoc fiber. The launching conditions in the latter experiment were arranged so that $W = 1$, and only the fundamental mode was excited. However, Guttmann *et al.*[7] have shown that, if GaAs lasers are used to excite these new Selfoc fibers, the launching is again mismatched ($W \ll 1$); they observed large dispersion (~13 psec/m). The degree of mismatching in the two types of Selfoc fibers is different with the same laser as their core diameters, relative index differences, and refractive index profiles are different.[2] Hence, the characteristic spot size is different in each type of fiber. It is now well known that the refractive index profile affects the total dispersion, as shown by various authors (see, for example, Refs. 11–13).

Therefore, the bandwidth of the Selfoc fibers will be determined by launching conditions as the mode mixing is small. This has been shown by Guttmann *et al.*,[7] who obtained a linear dependence of dispersion with lengths up to 700 m. (Hence, our dispersion results obtained with 60 m at 694 mm can be extrapolated to ~20 nsec/km.) With mode mixing, the dispersion increases as the square root of fiber length. The very small dispersions in Selfoc fibers can still be obtained with GaAs lasers but at the expense of simplicity by using Selfoc lenses[2] that transform the laser output and hence obtain the condition $W = 1$ at launching. Hence the use of these fibers and indeed all other graded-index fibers,[12,13] in practical fiber optical communication systems, can be versatile. Initially, if the demand for bandwidth is not high, simple butt launching with GaAs lasers can be used. Later, as the demand increases, the launching conditions only need to be altered with suitable packages containing the necessary transforming lenses. A corresponding alteration in the terminal electronics is necessary to obtain a high-capacity link.

Conclusion

We measured pulse dispersion in conventional Selfoc fibers and found that, under greatly mismatched launching conditions easily accomplished with a ruby laser for the first time, the dispersion was large, equivalent to ~20 nsec/km. This was in good qualitative agreement with theoretical predictions.

The work[6] was carried out while I was at Southampton University, and I thank W. A. Gambling for the facilities provided and for many stimulating discussions, D. N. Payne for pulling the fibers, and Nippon Sheet Glass Company for the Selfoc rods. I am especially indebted to G. D. Sims, now at Sheffield University, for his encouragement and advice at all times.

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